

# Monte carlo study of the physics performance of a digital hadronic calorimeter

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**ABSTRACT:** A digital hadronic calorimeter using MICROMEGAS as active elements is a very promising choice for particle physics experiments at future lepton colliders. These experiments will be optimized for application of the particle flow algorithm and therefore require calorimeters with very fine lateral segmentation. A  $1\text{ m}^2$  prototype based on MICROMEGAS chambers with  $1 \times 1\text{ cm}^2$  readout pads is currently being developed at LAPP. The GEANT4 simulation of the physics performance of a MICROMEGAS calorimeter is presented. The main characteristics, such as energy resolution, linearity and shower profile, have been carefully examined for various passive materials with pions over a wide energy range from 3 to 200 GeV. The emphasis is put on the comparison of the analog and digital readout.

**KEYWORDS:** Calorimeters, Detector modelling and simulations, Micropattern gaseous detectors, Large detector systems for particle and astroparticle physics.

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## 1. Introduction

Future particle physics experiments at the International Linear Collider (ILC) [1] will employ the Particle Flow Algorithm (PFA) to reach a jet energy resolution of  $30\%/\sqrt{E}$ . In order to achieve an optimal PFA performance, a highly granular hadronic calorimeter with a good shower separation is required. One of the suitable and affordable choice for an active part of the hadronic calorimeter is a thin gaseous detector with embedded *digital* (1-bit) or *semi-digital* (2-bit) readout. This concept allows the construction of the so-called Digital Hadronic CALorimeter (DHCAL) with very fine granularity (a cell size of about  $1\text{ cm}^2$ ) providing high MIP efficiency, low hit multiplicity as well as negligible performance degradation due to high dose rates, hadronic showers and aging.

One of the promising candidate for a DHCAL is the MICRO MESH Gaseous Structure (MICROMEGAS) which is a micro-pattern gaseous detector [2]. Prototypes with  $1 \times 1\text{ cm}^2$  anode pads, currently under development at LAPP, consist of a commercially available  $20\mu\text{m}$  thin woven stainless steel mesh which separates the 3 mm drift gap from the  $128\mu\text{m}$  amplification gap filled by an Argon/Isobutane (95/5) gas mixture. The readout electronics is embedded on the PCB below the anode, and thus creates a compact detector of 8 mm thickness. The sampling calorimeter equipped with such a detector is used for this study. This allows the first qualitative view on DHCAL global performances.

## 2. Calorimeter geometry and simulation tools

The geometry of the hadronic calorimeter, originally proposed for the SiD detector [4], was adapted for this study with various absorber materials (Fe, W, and Pb). The depth of the calorimeter, which is in SiD design  $4.5\lambda$  (40 absorber plates) was extended up to  $9\lambda$  (80 absorber plates) and hence the results obtained may also serve for the CLIC detector [5] which operates at a higher center-of-mass energy. As an active medium the MICROMEGAS detector has been chosen and the prototype geometry described above was implemented in the simulation. The absorber thickness in terms of interaction length  $\lambda$  is equal for all three absorbers, and therefore the total length of the calorimeter varies depending on the passive material. In case of Fe absorber, where two 2 mm thick steel cover plates of the MICROMEGAS chamber are supposed to be a part of the passive layer, the total calorimeter length is 200 cm. For W and Pb absorbers the steel covers were replaced by aluminum ones and thus the total length is about 170 cm and 239 cm, respectively. A lateral size of  $200 \times 200 \text{ cm}^2$  is equal for all three calorimeters.

Monte Carlo data for negative pions in a wide energy range from 3 to 200 GeV were generated by a GEANT4-based simulator SLIC with LHEP physics list. The generated data, around 20,000 events per energy for each calorimeter configuration, were subsequently reconstructed and analyzed using the org.lcsim framework [6]. Since the conversion from energy deposited in 3 mm gas gap to charge and electronics digitization were not included in the simulation, the so called *analog* and *digital* readout represent the deposited energy (in MeV) in gas gap or the number of counted hits<sup>1</sup> in  $1 \times 1 \text{ cm}^2$  cells, respectively. Both quantities are considered only when a readout threshold of 0.1 MIP MPV is reached.

## 3. Energy shower profile

### 3.1 Longitudinal and lateral shower profile

Longitudinal and lateral energy shower profiles were studied with various absorber materials in a wide energy range for both readouts.

The longitudinal shower profile is a sum of deposited energy in 3 mm gas gap or number of counted hits for all fired cells in one calorimeter layer versus calorimeter depth expressed in  $\lambda$  or number of layers. The results follow the expected behavior. First, the shower maximum, due to the progressive shower development depending on the energy of the incident particle, is getting deeper with increasing energy of primary pions (see Fig.1 top left). Second, the maximum is deeper for Fe absorber in comparison with W and Pb absorbers. This is consequence of the higher Z number and smaller  $X_0/\lambda$  ratio for W and Pb absorbers in comparison with Fe absorber (see Fig.1 top right).

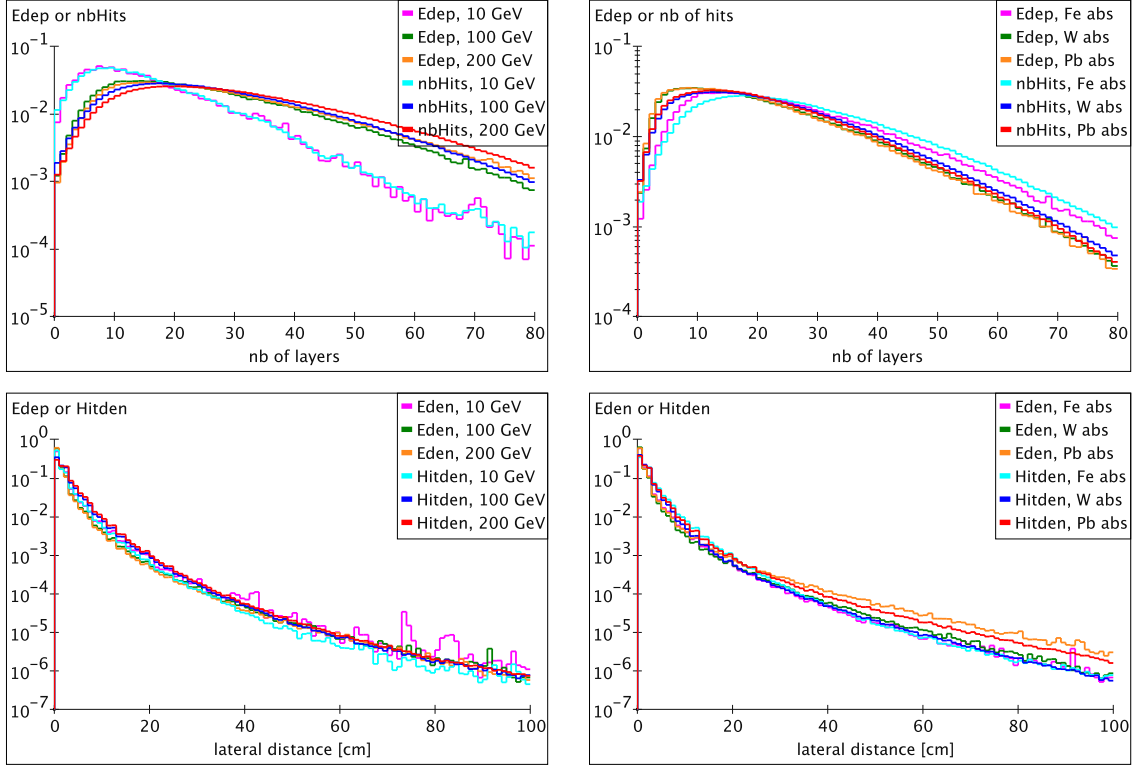
The comparison of analog and digital readout shows that longitudinal shower profiles are very similar for lower pion energy. For higher energy a shift (the shower maximum is deeper for digital with respect to analog readout) for higher energy has been observed for all three absorbers (see Fig.1 top). The shift, which is probably due to the saturation, is getting to be more important with increasing pion energy.

The lateral shower profile, described as the energy or hit density (i. e. deposited energy or number of counted hits per unit area) as a function of radial distance from beam axis, shows an

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<sup>1</sup>One hit is counted only when the deposited energy in a cell is higher than a given threshold

expected narrow core where mainly the electromagnetic component of the hadronic shower contributes. The core is surrounded by a gradually decreasing halo for which the hadronic component is responsible (see Fig.1 bottom). Similar behavior has been found for Fe and W absorbers in comparison with Pb showing slightly higher density for larger lateral distance. Also a shift between analog and digital readout has been found for lateral profile and can be explained by the same reason as in case of the longitudinal shower profile.

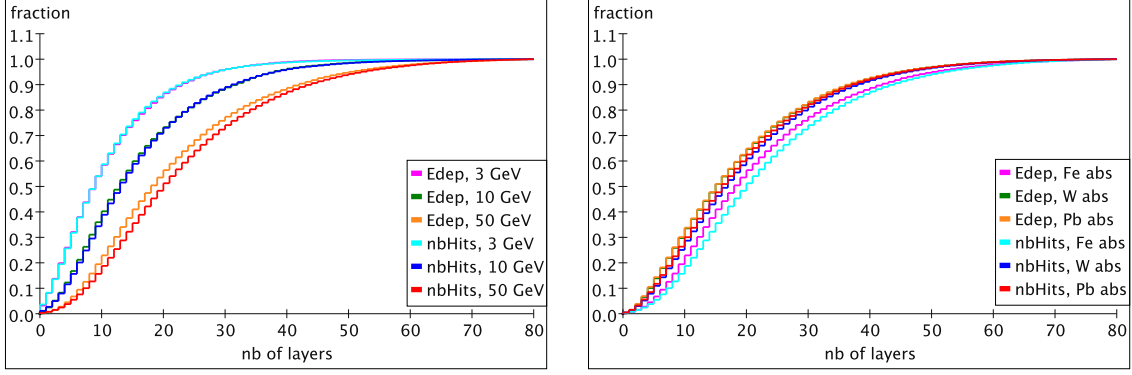


**Figure 1.** Longitudinal (top) and lateral (bottom) shower profiles for analog ( $E_{dep}$  or  $E_{den}$ ) and digital ( $nbHits$  or  $Hitden$ ) readout. The profiles on the left are for Fe absorber and for different pion energies. The profiles on the right are for 100 GeV pions and various absorbers. The distributions are normalized to 1.

### 3.2 Longitudinal fractional deposited energy

The longitudinal fractional deposited energy shows the fraction for a calorimeter of chosen depth (in  $\lambda$  or number of layers) with respect to the maximal calorimeter depth ( $9\lambda$  or 80 layers). For primary pions, which deposit almost 100% of their energy in  $9\lambda$ , the fractional deposited energy can be approximately equal to the energy containment. If this is assumed to be true for 50 GeV pions, the 95% energy containment can be reached with calorimeter having 50 layers (about  $5.6\lambda$ ) equipped with Fe absorber or 45 layers (about  $5\lambda$ ) in case of W or Pb absorbers (see Fig.2). In Fig.2, the shift between analog and digital readout is also seen, which is linked to the effect dis-

cussed above. This shift can lead to an underestimation of the calorimeter depth if only information from digital readout is considered.



**Figure 2.** Longitudinal fractional deposited energy in calorimeter for analog ( $E_{dep}$ ) and digital ( $nbHits$ ) readout for Fe absorber and different pion energies (left), and for various absorbers and 50 GeV pions (right).

## 4. Energy resolution and linearity

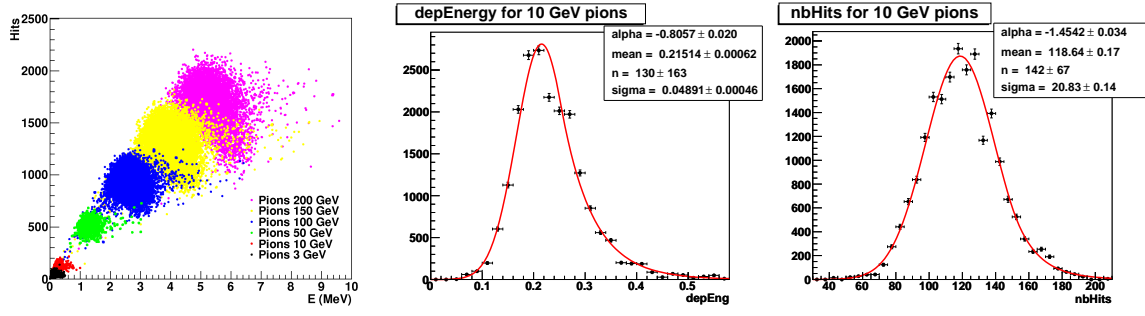
### 4.1 Deposited energy in analog and digital mode

The energy measured in a digital calorimeter, where only cells with energy above a chosen threshold are counted, is based on the very simple idea that the number of hits (fired cells) is directly proportional to the energy deposited in active medium and thus to the total energy absorbed in the calorimeter. The correlation between energy deposited in active medium (3 mm of gas) and number of counted hits for calorimeter with Fe absorber and for pion energy from 3 to 200 GeV is shown in Fig. 3 left.

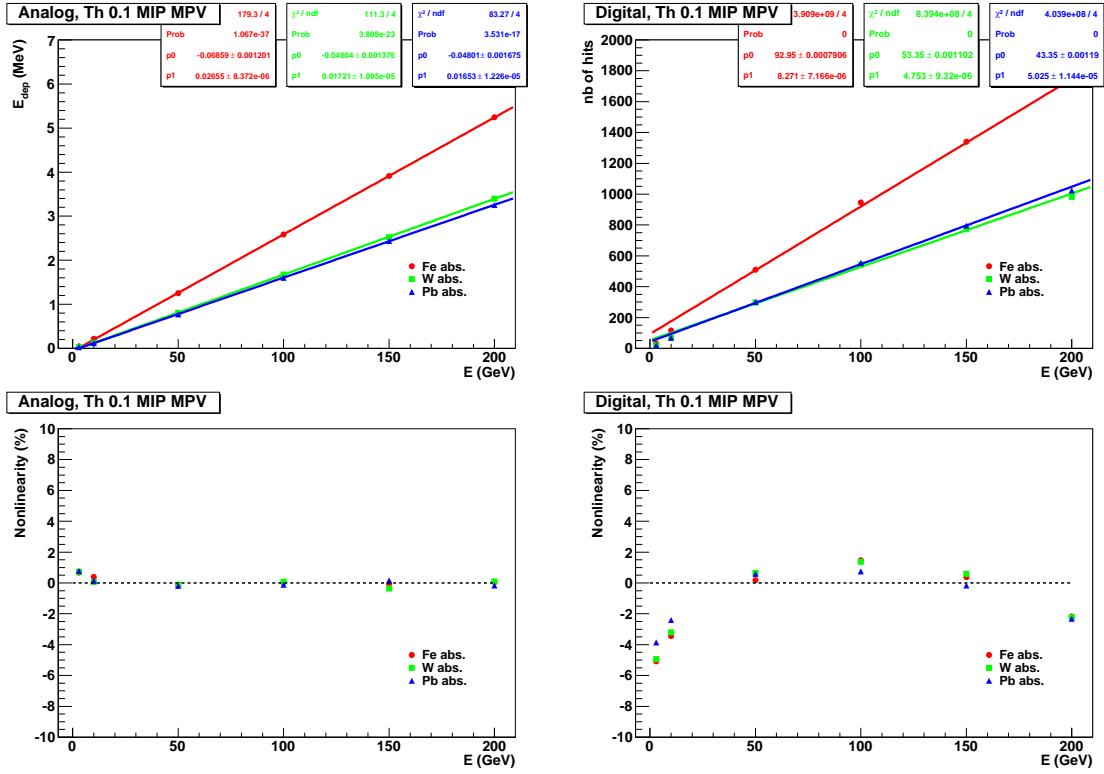
A distribution of the energy measured in hadronic calorimeter with gaseous detector presents significant right-hand tail due to the large Landau fluctuations in energy deposition in gas (see Fig. 3 middle). The digital readout leads to the suppression of these fluctuations, and consequently to an improvement of the energy resolution (see Fig. 3 right). On the other hand, the energy resolution at higher energies in digital mode is affected by saturation of the number of counted hits (see Fig. 4 right).

### 4.2 Response and linearity

The linear relation between calorimeter response and energy of primary pions for analog and digital readouts is shown in Fig. 4 top. The amount of energy deposited or number of hits is significantly higher in case of Fe absorber which is due to its longer  $X_0$ . The higher number of hits in case of Fe absorber and the properties of this material ( $X_0$ ,  $\lambda$ ) have a positive impact on the energy resolution described in following section.



**Figure 3.** Left: Correlation between deposited energy in Fe calorimeter and number of counted hits for pions energies. Middle and right: Distributions of deposited energy (analog readout) and number of counted hits (digital readout) in calorimeter with Fe absorber for 10 GeV pions.



**Figure 4.** Calorimeter response (top) and full scale non-linearity (bottom) for analog (left) and digital (right) readout and for various absorber materials.

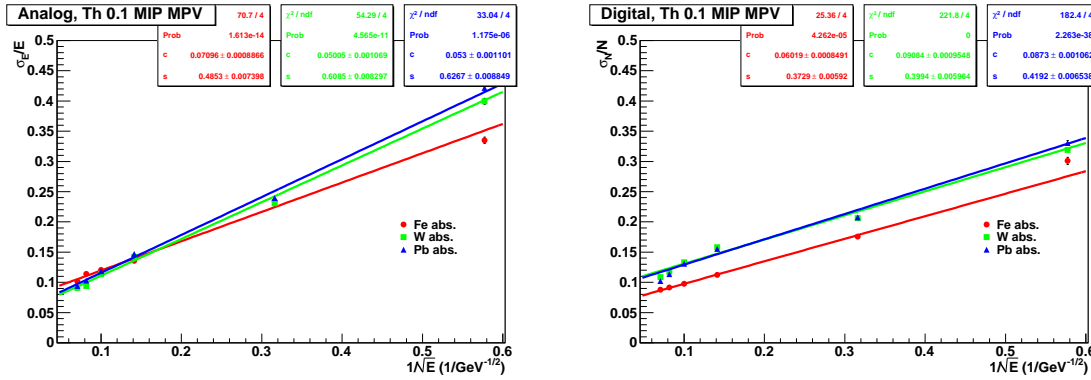
The linearity of the response was quantified by the full-scale non-linearity, i.e. the residuals of the linear fit of the response vs pion energy divided by the response of the higher primary pion energy (200 GeV). As can be seen in Fig. 4 bottom, the non-linearity behaves similar for all the absorbers and is within  $\pm 1\%$  for analog and  $\pm 5\%$  for digital readout, respectively. The worse

linearity for digital readout can be due to a saturation effect, when the number of hits does not follow increasing energy of the incident particles. This could be improved by adding one or two more thresholds (*semi-digital* readout).

### 4.3 Energy resolution

The energy resolution as a function of pion energy for various absorber materials and different readouts is displayed in Fig.5. The standard parametrization,  $\sigma_E/E = S/\sqrt{E} \oplus N/E \oplus C$ , for energy resolution as a function of incident particle is used in order to extract and evaluate the stochastic  $S$  and constant  $C$  terms (numeric values of these parameters are shown in Fig.5). Since any kind of noise is not present in the simulation, the noise term  $N$  in parametrization is not taken into account.

In case of analog readout, the energy resolution is similar for W and Pb absorbers and slightly different for Fe absorber as is shown in Fig.5 left. An identical behavior has been found for W and Pb absorbers with digital readout (see Fig.5 right). Comparing analog and digital readout for these absorbers, it has been observed that analog readout performs always better at high energy. This is a consequence of the suppression of Landau fluctuations and the saturation, respectively. On the other hand, the energy resolution for Fe absorber with digital readout is superior over the whole energy range as a consequence of the higher number of counted hits due to the longer  $X_0$  and larger  $R_M$  of Fe with respect to W and Pb.



**Figure 5.** Energy resolution as a function of reciprocal square root of pion energy for analog (left) and digital (digital) readout and for various absorber materials.

## 5. Summary and conclusions

The topology of the hadronic shower can be well described also in digital mode. Small difference in shower profiles between analog and digital mode have been found. The energy resolution for digital in comparison with analog readout tends to be superior for lower and inferior for higher energy. The linearity has been found always better for analog in comparison with digital readout.

Generally, it can be concluded that the presented Monte Carlo study has proved that a DHCAL concept, with respect to the basic performance characteristics, fulfills linear collider detector requirements. A difference in performance between digital and analog approaches has been identified and will be a subject of further investigation.

## References

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